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# The role of bioenergy and biochemicals in CO<sub>2</sub> mitigation through the energy system – a scenario analysis for the Netherlands

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## Abstract

Bioenergy as well as bioenergy with carbon capture and storage are key options to embark on cost-efficient trajectories that realize climate targets. Most studies have not yet assessed the influence on these trajectories of emerging bioeconomy sectors such as biochemicals and renewable jet fuels (RJFs). To support a systems transition, there is also need to demonstrate the impact on the energy system of technology development, biomass and fossil fuel prices. We aim to close this gap by assessing least-cost pathways to 2030 for a number of scenarios applied to the energy system of the Netherlands, using a cost-minimization model. The type and magnitude of biomass deployment are highly influenced by technology development, fossil fuel prices and ambitions to mitigate climate change. Across all scenarios, biomass consumption ranges between 180 and 760 PJ and national emissions between 82 and 178 Mt CO<sub>2</sub>. High technology development leads to additional 100–270 PJ of biomass consumption and 8–20 Mt CO<sub>2</sub> emission reduction compared to low technology development counterparts. In high technology development scenarios, additional emission reduction is primarily achieved by bioenergy and carbon capture and storage. Traditional sectors, namely industrial biomass heat and biofuels, supply 61–87% of bioenergy, while wind turbines are the main supplier of renewable electricity. Low technology pathways show lower biochemical output by 50–75%, do not supply RJFs and do not utilize additional biomass compared to high technology development. In most scenarios the emission reduction targets for the Netherlands are not met, as additional reduction of 10–45 Mt CO<sub>2</sub> is needed. Stronger climate policy is required, especially in view of fluctuating fossil fuel prices, which are shown to be a key determinant of bioeconomy development. Nonetheless, high technology development is a no-regrets option to realize deep emission reduction as it also ensures stable growth for the bioeconomy even under unfavourable conditions.

**Keywords:** bioeconomy, CO<sub>2</sub> mitigation, cost-minimization, emerging sectors, scenario analysis

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## Introduction

In line with long-term climate targets agreed upon at the 21st Conference of Parties in Paris (UNFCCC, 2015), the European Union (EU) set out to increase its renewable energy supply to 27% and to achieve 40% greenhouse gas (GHG) emission reduction by 2030 compared to 1990, towards a 80–95% reduction by 2050 (EC, 2015). Large-scale modern bioenergy deployment, carbon capture and storage (CCS), and their combination (bioenergy with carbon capture and storage; BECCS) are among the key energy supply and carbon mitigation options required to embark on cost-efficient trajectories

that pursue climate goals (IPCC, 2014; Rose *et al.*, 2014; Matthews *et al.*, 2015; Winchester & Reilly, 2015).

Within the EU, bioenergy supply is shown to be significant in sectors such as heat and road transport (Stralen *et al.*, 2013). Increasingly, there is evidence to suggest that emerging bioeconomy sectors such as aviation and chemicals, which have few or no other renewable alternatives than biomass, and CCS and BECCS will also be needed. Based on mid-term demand projections, biochemicals and bioplastics (frequently referred to as nonenergy uses of biomass) may consume 9–24% of global biomass demand by 2050 (Piotrowski *et al.*, 2015). Other studies show 15–17% of total biomass to be used for nonenergy applications (18–27 EJ yr<sup>-1</sup>) and to supply approximately 7–11 EJ yr<sup>-1</sup> of global nonenergy biomass products (Daioglou *et al.*, 2015). In other

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sectors, such as aviation, the EU has the ambition to reach 88 PJ (2 Mt, assuming 44 GJ t<sup>-1</sup> heating value) renewable jet fuel (RJF) consumption, which is about 3.7% of its projected jet fuel demand by 2020 (EC, 2003, 2011). These new sectors are particularly relevant for countries with relatively large refining capacity and energy intensive industry such as the Netherlands. The Netherlands consumes about a quarter of its total final energy for nonenergy purposes (585 PJ in 2013, CBS, 2016) and within the EU, it has the largest petrochemical capacity next to Germany (OGJ, 2012). Regarding emission reduction, at a global level, BECCS would need to contribute between 2 and 10 Gt CO<sub>2</sub> yr<sup>-1</sup> in 2050 in order to ensure compliance with the 2 °C target (4–22% of the 1990 baseline; Fuss *et al.*, 2014). Based on Rose *et al.* (2014), modern bioenergy supply may reach 37% (or up to about 250 PJ) over total primary energy supply by 2050 and is largely combined with BECCS. Despite these expectations, comprehensive assessments of extended bioeconomy sectors (i.e. aviation, chemicals) in energy system models, interactions with other renewable energy sources (RES; e.g. wind or solar) and mitigation technologies (i.e. CCS, BECCS) at a national or regional level, are scarce.

Such an analysis requires an integrated energy systems assessment framework that takes into account emerging bioeconomy sectors next to modern bioenergy and that addresses key factors of uncertainty with sufficient level of detail on the energy system's structure and on the complex flows of the petrochemical industry. To obtain the necessary detail, we focus on the energy system of the Netherlands, which requires a significant transformation for the country to meet its renewable energy and GHG mitigation goals, in line with the EU targets (Roelofsen *et al.*, 2016; Vuuren *et al.*, 2016). Albeit having an efficient agricultural sector, the Netherlands is dependent on biomass imports in order to support large-scale bioeconomy developments, similar to the EU (Stralen *et al.*, 2013). This is deemed possible due to its advanced logistics infrastructure. While modelling outcomes are pertinent to the Netherlands, they are useful to provide insights in the implications of large-scale bioeconomy developments also in the EU.

Our earlier study incorporated the chemicals and aviation sector in a national energy systems model of the Netherlands and demonstrated that biomass conversion technologies may be cost-competitive compared to other fossil and renewable alternatives by 2030 to achieve renewable energy goals (Tsiropoulos, 2016). With respect to biomass conversion, industrial heat from biomass, lignocellulosic sugar production, biochemicals from sugar fermentation and Fischer–Tropsch (FT) road transport fuels from solid biomass gasification were shown to be most promising options. These findings are in line with

other research (Ren & Patel, 2009; Ren *et al.*, 2009; Saygin *et al.*, 2013, 2014; Gerssen-Gondelach *et al.*, 2014). However, our earlier study also showed that while the renewable energy technology portfolio was stimulated by renewable energy policies, emission reduction targets of 40% by 2030, compared to 1990, were not met. Therefore, additional insights are needed as to the required preconditions to pursue those targets. One limitation of the abovementioned study is that it only assessed the influence of technology development as a factor of future uncertainty, while other crucial parameters such as varying fossil fuel prices and availability of low-cost biomass in combination with technological progress may also affect bioeconomy developments and the pathways to emission reduction. These uncertainties need to be assessed under a technology-neutral setting, with climate policy such as a CO<sub>2</sub> tax being the only driver for the deployment of a cost-optimal technology portfolio.

Such an assessment is performed in the present study using a national cost-minimization linear programming model developed for the Netherlands (MARKet ALlocation MARKAL-NL-UU; Tsiropoulos, 2016) that apart from technology characterization of the fossil energy system also includes key biomass conversion technologies, other renewables and mitigation options (CCS, BECCS). Using scenario assessment for a combination of uncertainty factors on technology development, biomass cost-supply and fossil fuel prices, we estimate the achieved CO<sub>2</sub> emission reduction, the required technology portfolio, the demand for biomass and supply of bioenergy and biochemicals in each case.

## Materials and methods

We focus on bioeconomy activities that relate with the energy system and the chemical industry (i.e. bioenergy, biochemicals) that have the potential to replace fossil fuels in the energy system. Other economic activities based on biomass, for example food, feed, traditional biomass uses (lumber products), are not included in the framework. We translate key parameters of future uncertainty of the bioeconomy development (technology development, biomass cost-supply, fossil fuel prices) to scenarios and then perform scenario analysis by comparing outputs derived from a cost-minimization linear programming energy system model developed for the Netherlands.

## Model

The MARKAL-NL-UU applied in this study uses cost-minimization linear programming techniques to define the technology portfolio required to meet demand for energy (electricity, heat, fuels) and chemicals that lead to least total system costs. The model can be described by three core modules: energy supply, energy and chemicals conversion, and energy and chemicals demand.

The electricity sector and the CCS technology portfolio for the Netherlands are described in van den Broek *et al.* (2008, 2011). The model's extension to the road transport sector is included in van Vliet *et al.* (2011). Finally, emerging bioeconomy sectors have been included by Tsiropoulos (2016). The technology portfolio of MARKAL-NL-UU for electricity, heat, road transport and jet fuels, and chemicals is described in Tables S1–S3.

### Energy supply

In the energy supply module, cost-supply trajectories of fossil, nuclear and biomass resources are included. For fossil fuels, the price develops according to the International Energy Agency World Energy Outlook 2015 (IEA-WEO) New Policies Scenario (OECD/IEA, 2015), unless stated otherwise. Fossil fuel price variation is a key aspect of future uncertainty, which is taken into account in scenario assessment (section 'Fossil fuel prices').

Biomass cost-supply curves are estimated based on the sourcing region (domestic, European, global) and are specified for different biomass types. Road-side costs and potentials for biomass are determined for 2010–2030, based on the Intelligent Energy Europe project Biomass Policies (Elbersen *et al.*, 2015). In this database, biomass represents the net available potential for bioenergy, thereby excluding competition with traditional sectors such as food, feed and fibres. Costs refer to market prices for already traded biomass types and to road-side costs for biomass markets that are not developed (Elbersen *et al.*, 2015). To these costs, we add transport costs to the Netherlands using a geographical explicit biomass intermodal transport model (BIT-UU; described in Hoefnagels *et al.*, 2014a,b). Biomass transport costs, calculated at Nomenclature of territorial units for statistics 2 level, are aggregated based on the weighted average for 4 EU regions as described in Tsiropoulos (2016). From the regional biomass supply potential, it is assumed that approximately 5% may be available for export to the Netherlands, based on the share of the Dutch total primary energy supply over the EU's to 2030. In OECD/IEA (2014), the EU demand is 61 EJ under the 450 ppm scenario in 2030. For comparison, the Dutch demand is 3.2 EJ and the assumed biomass in 2030 is about 430 PJ or 13% of the country's total primary energy supply.

These assumptions may lead to conservative biomass cost-supply estimates for two reasons. Firstly, transport costs are based on wood chip logistics, thereby ignoring cost-efficiency gains that can be achieved if biomass is densified at the sourcing region, for example, to wood pellets. Secondly, each country may supply larger potential than the 5% we allocated if markets are well-developed. These factors are addressed in scenarios (section 'Biomass cost-supply').

Next to biomass from EU sources, five commodities from extra-EU sources are included, namely raw sugar, wood pellets, first- and second-generation ethanol, vegetable oil and biodiesel. Ultimately, it depends on the total production system costs, which include feedstock and conversion, to indicate the cost-optimal use of intra-EU or extra-EU resources. A total of 400 PJ of solid biomass and 50 PJ of liquid biomass are assumed to be available for imports to the Netherlands. Such

potential is approximately 26 Mt in wood pellet equivalent, which is rather large considering that it corresponds to global wood pellet consumption in 2015 (about 25.5 Mt; AEBIOM (2015)). However, there is sufficient evidence that suggests that these volumes may be available (Chum *et al.*, 2011; Ganzevles, 2014; Smeets, 2014). The influence of extra-EU import is assessed in a separate scenario, which assumes that only domestic and intra-EU biomass is available (section 'Biomass cost-supply'). CO<sub>2</sub> emissions from biomass production in the Netherlands contribute to the national total CO<sub>2</sub> emissions. Indirect emissions from extraction and import of fossil resources to the Netherlands or biomass production outside the Netherlands do not contribute to the national total.

### Technologies for energy and chemicals conversion

The model includes a large portfolio of fossil (natural gas, oil, coal), nuclear and renewable energy technologies (e.g. biomass conversion, wind turbines, photovoltaics) that convert primary resources to electricity, heat, fuels for the energy system, and feedstocks or end products for the fossil-based and bio-based chemical industry. Fossil, nuclear and renewable energy conversion technologies are characterized based on their cost structure at a specific year and scale and technical parameters (process energy input, process efficiency). Annual costs consist of capital investment costs (e.g. process components, buildings, contingency), fixed costs (operation and maintenance, administrative costs) and variable costs (e.g. feedstock, utilities, labour). CO<sub>2</sub> emissions from conversion of primary to secondary energy carriers represent the emissions of the energy system, including industrial process emissions. Non-CO<sub>2</sub> GHG emissions that are not associated with the energy system are not included in the boundaries of the model (e.g. methane emissions by activities in agriculture). These represent approximately 16% of national total GHG emissions in 2014 (Table S9).

Biorefineries (biochemical and thermochemical) are also included in the model. Conventional coal gasification and FT-synthesis to fuels is excluded as an option. Similar to other multi-output processes such as combined heat and power plants, biorefineries deliver outputs to several sectors (e.g. to fuels and electricity) as opposed to, for example a wind turbine, which delivers only to the electricity sector. This enables access to different demand markets in direct competition with other technologies thus reducing total system costs.

An overview of technologies is presented in Tables S1–S3. The cost structures are described in Tables S4–S7, and the cross-sectoral flows are described in Tsiropoulos (2016). Technology development is rather uncertain and therefore assessed by scenarios in this study (section 'Rate of technology development and technology diffusion'; Figs S2 and S3).

### Energy and chemicals demand

The final energy demand for electricity, heat, and the production volume of chemicals and aviation fuels is exogenously determined and specified for the Netherlands based on demand projections from EC (2003), Saygin *et al.* (2009), Chèze

*et al.* (2011) and ECN (2015) as described in Tsiropoulos (2016). The final demand for road transport (liquid fuels, electricity) is endogenously calculated based on the assumed demand for vehicle-kilometres (van Vliet *et al.*, 2011). While projections for key energy applications such as heat and electricity are relatively stable over time, for nonenergy uses future demand poses higher uncertainties. This in turn can determine to a large extent the deployment potential of biochemicals. In an additional scenario, we assume that the chemical sector follows a negative growth rate trajectory (section Other sensitivity scenarios). Demand projections are provided in Table S8 and Fig. S1.

## Scenarios

Scenario analysis of 'if-then' propositions is shown to be useful to the extent that it provides insights that improve strategic management by better understanding uncertainties and robustness of decisions under a wide range of possible futures. These can be stirred by strategies but can also be influenced by uncontrolled variables (Schwartz, 1996; Moss *et al.*, 2010).

*Baseline scenarios (Base)* in this study give a plausible indication on how the energy and nonenergy system may develop if no focus is placed on renewable energy and climate goals beyond 2020. We then deploy a set of scenarios that assess the effect of climate policies, namely a CO<sub>2</sub> tax that corresponds to meeting the 2 °C (OECD/IEA, 2015), in combination with bioeconomy strategies focused on the conversion and supply side.

*Policy context of scenarios. Scenario parameters to 2020:* To assess the cost-efficient contribution of biomass and other RES to CO<sub>2</sub> mitigation pathways, conversion technologies should compete on a level playing field. Scenarios that are technology-neutral avoid distortion caused by policies or support schemes (e.g. subsidies on specific technologies). However, up to 2020, binding policy goals at the EU level and national measures are already agreed and implemented. They include support to electricity, heat and road transport fuels up to 2020 and are assumed to be achieved in all scenarios. These include the following:

- the renewable energy share (14% for the Netherlands) and the biofuel target (10% including double-counting of biofuels from waste and residues, and contribution of renewable electricity in road transport by a factor 2.5; EU Renewable Energy Directive [RED]; EC, 2009);
- the retirement of old coal-fired power plants built before 1990 and wind deployment as part of national plans to meet the EU RED targets (SER, 2013);
- maximum of 25 PJ electricity produced by cofiring biomass in coal power stations (SER, 2013);

In addition, we assume an emission tax as part of the climate policies to 2020 (i.e. 15 € t CO<sub>2</sub><sup>-1</sup> in 2020), based on the IEA-WEO 2015 New Policies Scenario. The tax is applied to emissions from all sectors (i.e. including transport and residential heat).

*Scenario parameters from 2020 onwards.* Beyond 2020, all sectors compete on a level playing field. Therefore, cost-competitiveness of secondary energy carriers and chemicals is the only determinant of technology deployment, biomass contribution to demand and achieved CO<sub>2</sub> emission reduction.

In line with the EU Intended Nationally Determined Contribution, mid-term emission reduction (2030) needs to reach 40% compared to 1990 (EC, 2015). We use CO<sub>2</sub> tax as the only policy instrument that stimulates emission reduction based on the IEA-WEO 2015 450 ppm scenario. Tax levels are 42 € t CO<sub>2</sub><sup>-1</sup> in 2025 and 69 € t CO<sub>2</sub><sup>-1</sup> in 2030 (OECD/IEA, 2015). The CO<sub>2</sub> tax applies to generated emissions in the Netherlands, as opposed to the carbon content of fossil feedstocks used. For biochemicals, this entails that only savings from energy use in industry and process emissions are affected by the tax and contribute to CO<sub>2</sub> emission reduction, as large part of the carbon in biomass feedstock remains embedded in final biochemical products. Emission savings from biochemicals may occur outside the geographical boundaries of the Netherlands, at their end-of-life in demand regions. However, such savings are not assessed in this study. Similarly, GHG emission savings may be achieved in sectors other those of the energy system (e.g. reduction in methane emissions in agriculture). However, these are excluded from the scope of this study due to the dominant role of CO<sub>2</sub> emissions in climate change in the long-term and their direct relationship with the energy system (Vuuren *et al.*, 2016).

We assess fossil fuel prices and climate policy scenarios separately. The policy context beyond 2020 as described above is used in the *reference (Ref)*, *biomass cost-supply (LowBio, HighBio)* and *fossil fuel price scenarios (LowFos, HighFos)* (section 'Scenario definitions'; Table 1).

*Scenario definitions.* The emission mitigation pathways are based on key strategies for development of biomass production systems across the supply chain, from feedstock to conversion.

*Rate of technology development and technology diffusion (LowTech, HighTech).* Technology development based on learning and subsequent cost reductions can considerably influence the competitiveness of biomass conversion technologies. Technology costs decline by a constant factor with each doubling of cumulative capacity (BCG, 1968). However, this occurs at a global level, which is outside of the regional scope of this study. Incremental improvements over time such as in efficiency may also affect conversion costs. These factors are not endogenized in MARKAL-NL-UU. Therefore, we capture the uncertainty of technical progress on cost reduction in biomass conversion technologies and the role of BECCS to 2030 using two technology pathways that follow *low (LowTech)* and *high technology (HighTech)* development progress (Figs S2 and S3). These pathways vary technology parameters and assume different learning rates for biomass conversion. More specifically, the two scenarios differ in technology portfolio, rate of incremental improvements, year of technology availability and scales as described in detail in Tsiropoulos (2016). *LowTech* assumes that little support is provided to conversion technologies by means of stimulating research and development (R&D),

**Table 1** Overview of the scenarios assessed in this study. Baseline scenarios assume CO<sub>2</sub> tax up to 2020. All other variants assume CO<sub>2</sub> tax up to 2030

		Scenario variable: biomass cost-supply				
		Low-cost biomass	Reference-cost biomass	High-cost biomass		
Baseline (no CO <sub>2</sub> tax beyond 2020)	High technology development	n.a.*	HighTechBase	n.a.*	Reference fossil fuel price	Baseline (no CO <sub>2</sub> tax beyond 2020)
	Low technology development	n.a.*	LowTechBase	n.a.*	Reference fossil fuel price	
Scenario variable: technology development	High technology development (HighTech)	n.a.*	HighTech(RefBio_HighFos)	n.a.*	High fossil fuel price	Scenario variable: fossil fuel price
		HighTech (LowBio_RefFos)	HighTechRef†‡	HighTech(HighBio_RefFos)	Reference fossil fuel price	
	Low technology development (LowTech)	n.a.*	HighTech(RefBio_LowFos)†	n.a.*	Low fossil fuel price	
		n.a.*	LowTech(RefBio_HighFos)	n.a.*	High fossil fuel price	
		LowTech (LowBio_RefFos)	LowTechRef†‡	LowTech(HighBio_RefFos)	Reference fossil fuel price	
		n.a.*	LowTech(RefBio_LowFos)†	n.a.*	Low fossil fuel price	

\*Combination of scenarios is not assessed in the present study.

†Scenario variables used to assess the sensitivity of the biochemical sector in low chemical demand and delayed decommissioning of steam crackers.

‡Scenario variables used to assess the impact of complete closure of coal-fired power plants on CO<sub>2</sub> emissions.

fast deployment of 1st-of-a-kind plants, support to technologies to go beyond the valley of death, rapid scale up and so forth. On the other hand, *HighTech* assumes that these conditions are met through coordinated action of business, industry and governments.

To avoid supply of all demand in the transport sector by a single technology, we apply market constraints on second-generation technologies based on de Wit *et al.* (2010). Individual technologies can supply up to 10% of demand in 2030.

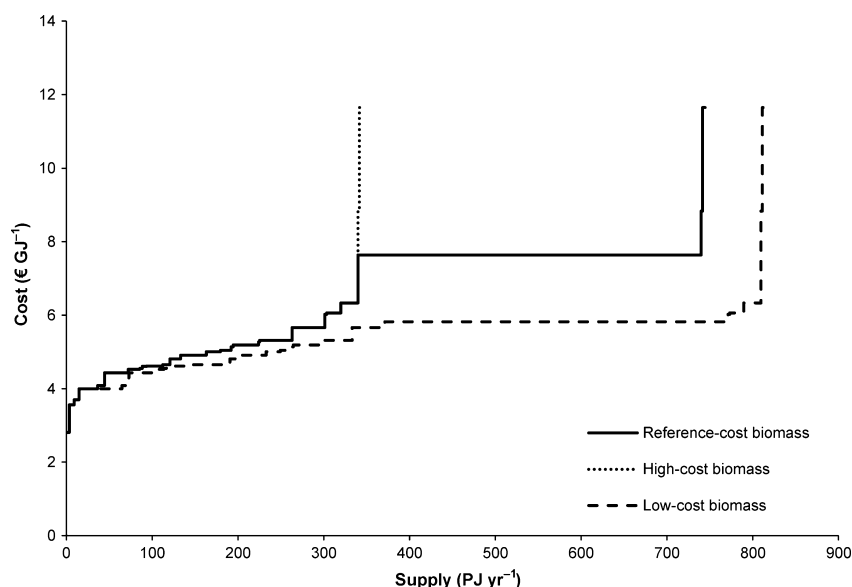
#### *Biomass cost-supply (LowBio, HighBio). Low-cost biomass:*

The extra-EU and intra-EU cost-supply of biomass in baseline and reference scenarios are conservative for two reasons. Firstly, the price of extra-EU wood pellets is based on mill-gate costs of around 6 € GJ<sup>-1</sup>. However, studies indicate that these can be as low as 3.9 € GJ<sup>-1</sup> (Uslu *et al.*, 2008) or 2.3–3.1 € GJ<sup>-1</sup> by 2030 (Batidzirai *et al.*, 2014) when low-cost biomass is used for pellets. These could be achieved, for example, using surplus or abandoned agricultural land for energy crops and intensification of agricultural productivity (de Wit & Faaij, 2009; Wicke, 2011). Secondly, the cost-price of intra-EU biomass delivered to the Netherlands, as assumed in this study, is conservative because transport costs are estimated based on wood chip logistics (section 'Energy supply'). The cost-competitiveness of biomass chains can improve if efforts focus on biomass

densification to reduce transport and handling costs (e.g. torrefaction and pelletization). Such efforts are assumed to take place in the *LowBio* scenario resulting to lower upstream cost-supply of solid biomass. The approach we used to estimate low-cost biomass supply curves for extra-EU and intra-EU biomass resources is presented in detail in S1.2 in Appendix S1.

*High-cost biomass.* As a consequence of worldwide increase in biomass demand, it is expected that global biomass trade will continue in the future, thereby allowing cost-efficient distribution of biomass from supply to demand regions. However, it is uncertain how trade and markets will develop. If the EU is the only region that supports bioeconomy developments, then EU demand regions like the Netherlands will have access only to intra-EU resources. The *HighBio* scenario assumes that extra-EU import of biomass is not possible, which decreases the total potential by 450 PJ compared to the reference. This effectively leads to increased costs of solid biomass as a large potential below 7.5 € GJ<sup>-1</sup> for solid biomass becomes unavailable.

The cost-supply curves of solid biomass used across the different scenarios are presented in Fig. 1. The cost-supply curves exclude energy maize, solid waste, fuelwood, landscape wood and road-side grasses, as unlike the solid biomass feedstocks included in Fig. 1, they are linked with specific end-use



**Fig. 1** Solid biomass cost-supply curves in the different scenarios of this study in 2030.

applications (e.g. energy maize with codigestion, solid waste with energy incineration and energy recovery and so forth).

**Fossil fuel prices (*LowFos*, *HighFos*).** Fossil fuel prices are uncertain, are subjected to change over time (OECD/IEA, 2015) and are key determining, but uncontrolled factor of the success or failure of bioeconomy development strategies and other RES. To capture the uncertainty that such variables may have on emission mitigation, we deploy the following scenarios:

- *LowFos*: To obtain insights into the magnitude of biomass and other RES development in an unfavourable environment, we use fossil fuel prices reported in IEA-WEO 2015 Low oil price scenario (OECD/IEA, 2015). Compared to the New Policies Scenario, these prices are lower approximately 35% for oil, 20% for natural gas and 6% for coal compared to the reference fossil fuel prices.
- *HighFos*: To obtain insights into the magnitude of biomass and other RES deployment under favourable conditions, a 50% higher fossil fuel prices is assumed compared to those of the New Policies Scenario reported at IEA-WEO 2015 (OECD/IEA, 2015).

The variation of fossil fuel prices is presented in Fig. 2.

### Other sensitivity scenarios

Several drivers, such as contraction of the economy or competition from other regions (Broeren *et al.*, 2014), may saturate or even decrease the production demand for chemicals assumed for the Netherlands over time. Future reduction in the demand for chemicals in combination with no decommissioning of existing steam cracking capacity in the Netherlands is assessed as an additional sensitivity scenario. A 10% reduction in demand for chemicals in 2030 compared to 2010 is assumed based on the reduction in the size of the Dutch petrochemical industry according to van Meijl *et al.* (2016).

Furthermore, in the EU, several governments consider reducing support on, divesting in or even dismantling coal-fired power plants as this may compromise the diffusion of other RES and CO<sub>2</sub> emission reduction goals (Nicola & Andresen, 2015; Yeo, 2015; Pieters, 2016; Sterl *et al.*, 2016). We assess this possible future in a scenario, which assumes that electricity from coal cannot be produced in the Dutch energy system after 2020.

Other studies show that the role of biomass in the energy system varies, depending on the electricity mix. With exogenously determined electricity supply from other RES ranging between 17% and 80% and strong climate policy, biomass use for power generation in Europe ranges between 2.5% and 33% (0.4–2.1 EJ) of total fuel use in 2050 (Brouwer *et al.*, 2016), without, however, taking competition by other sectors into account. Furthermore, improvements on energy efficiency could reduce heat demand in the industry and residential sector. This suggests that a large number of additional scenarios can be defined to investigate the sensitivity of the system and competition for biomass, which, however are excluded from this study.

### Indicators and overview of the modelling framework

For each scenario in Table 1 we assess the following:

- the final production output from RES per sector in 2030. For the energy sectors (electricity, heat, fuels), production output is expressed in final energy terms, while for the chemical sector it is estimated based on the lower heating value of biochemicals;
- the contribution of renewable energy on the total final energy produced by each sector;
- the renewable energy share (i.e. excluding the nonenergy use of the chemical sector);
- biomass demand that reflects total biomass consumption in primary energy terms, same as in Tsiropoulos (2016);

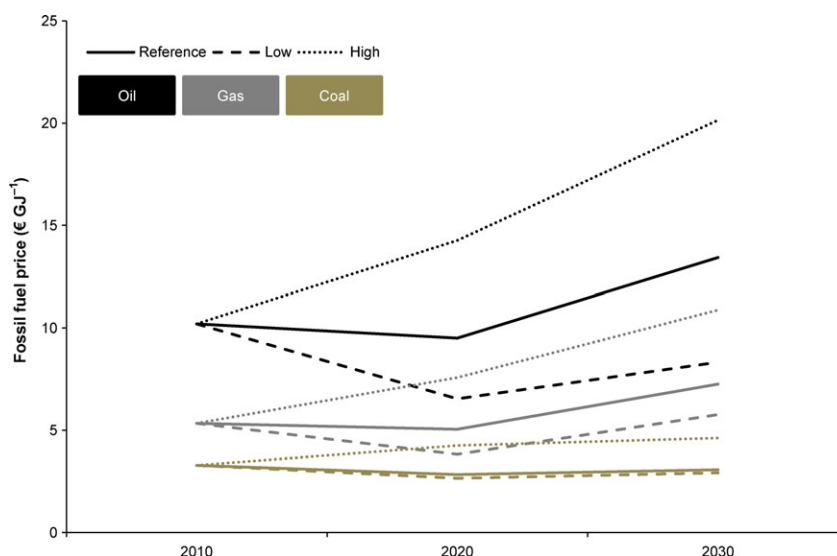


Fig. 2 Fossil fuel price in the reference scenarios and their fossil fuel price variants.

- the direct CO<sub>2</sub> emissions in the Netherlands related to the supply of energy services in all sectors and process emissions by industrial activities. Direct CO<sub>2</sub> emissions are those emitted in the Netherlands; they exclude emissions from production or extraction and transport of resources (biomass, fossil) to the Netherlands, consistent with IPCC (2006);
- total annual system costs in 2030, compared to *HighTechBase*.

Figure 3 presents an overview of the framework used in this study.

## Results

Final production from biomass and other RES, and their contribution to each sector are shown for the reference scenario in combination with the two technology development variants by bars (*HighTechRef*, *LowTechRef*), while the range of outcomes based on the biomass cost-supply and fossil fuel price scenarios is indicated with whiskers (Fig. 4). Outcomes for the baseline situation in combination with the technology development scenarios are presented with markers (*HighTechBase*, *LowTechBase*). Results are presented for 2030.

For the indicators renewable energy share (Fig. 5), biomass consumption (Fig. 6) and CO<sub>2</sub> emissions (Fig. 7), we present the influence of technology development in reference conditions (i.e. CO<sub>2</sub> tax) in comparison with the baseline for the period 2010–2030. As the results for the two technology development variants do not differ significantly in 2020, we only show the 2010–2030 trajectory of the *HighTech* scenario for the biomass cost-supply and the fossil fuel price variants. For comparison, we include results for the *LowTech* scenario in

2030. Apart from the range due to the variation of scenario parameters, results also include the consumption under baseline and reference conditions. For all scenarios, the difference of their total annual system costs from *HighTechBase* is plotted against the corresponding difference in total direct CO<sub>2</sub> emission reduction in 2030. Results with sector-specific assumptions are presented in section ‘Other scenarios’ (Figs 10 and 11).

All results per scenario and sector are presented in Tables S10–S12.

## Renewable energy

Final production from renewable resources was estimated to be between 460 and 510 PJ in 2030 and does not differ significantly between *HighTechRef* and *LowTechRef* (Fig. 4a), thereby indicating that under reference assumptions on CO<sub>2</sub> tax, biomass cost-supply and fossil fuel price, technology development is not the only driver for cost-efficient supply of bioenergy and other renewable energy. Other drivers include cost-supply of biomass and fossil fuel prices as indicated by the whiskers in Fig. 4 (range 230–745 PJ). The renewable energy output (Fig. 4b) corresponds to a 23–24% share on final energy consumption excluding chemicals or to a 18–20% share on final energy consumption including chemicals. More than two-thirds (73–79%) of renewable energy output is attributed to biomass (Fig. 4a, b), which is higher than the anticipated contribution of biomass in the energy system based on the EU RED targets for 2020 (Rijksoverheid, 2010; Stralen *et al.*, 2013). This is primarily due to the ambitious climate policy assumed in this study beyond 2020 (by means of high CO<sub>2</sub> tax). In addition, as in this study the CO<sub>2</sub> tax also applies to



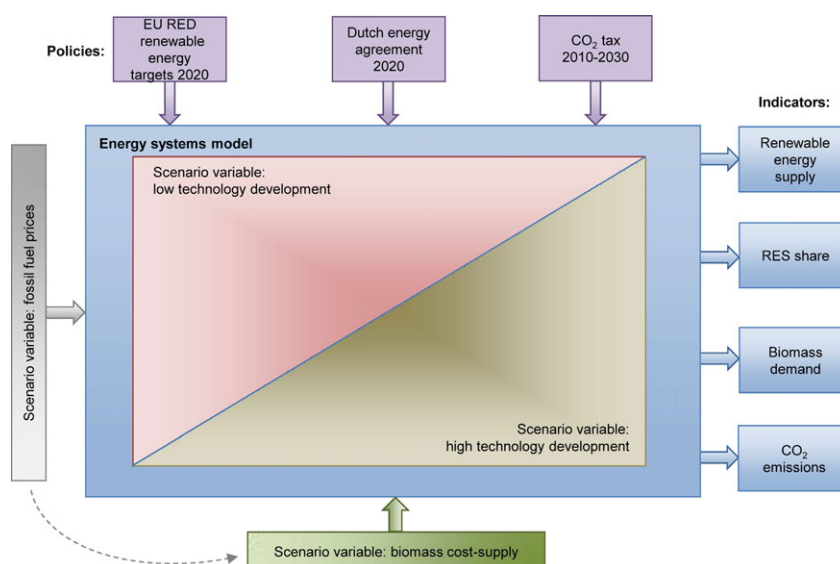


Fig. 3 Modelling framework used in the present study.

emissions by transport, it results to high biofuel output especially in *HighTechRef*. The remainder mainly represents renewable electricity by other renewable resources (wind and solar).

At a sector level and in absolute terms, technology development scenarios affect the supply of industrial biomass heat, biofuels and biochemicals (bars in Fig. 4a). These are also found to be the sectors with the largest bio-based output. Under *LowTech* assumptions, it is more cost-effective to supply solid biomass in industrial biomass boilers and produce heat as biofuel production technologies for road transport and RJF are not cost-competitive. Under *HighTech*, the reverse occurs as biomass conversion technologies to biofuels for road transport and aviation become cost-competitive. The trade-off between biomass heat and biofuel output is also observed in Tsiropoulos (2016) when using different policy assumptions beyond 2020. Electricity from biomass remains small (20–50 PJ; primarily from biorefineries, cofiring and municipal solid waste incineration), as wind becomes the key supplier of renewable electricity.

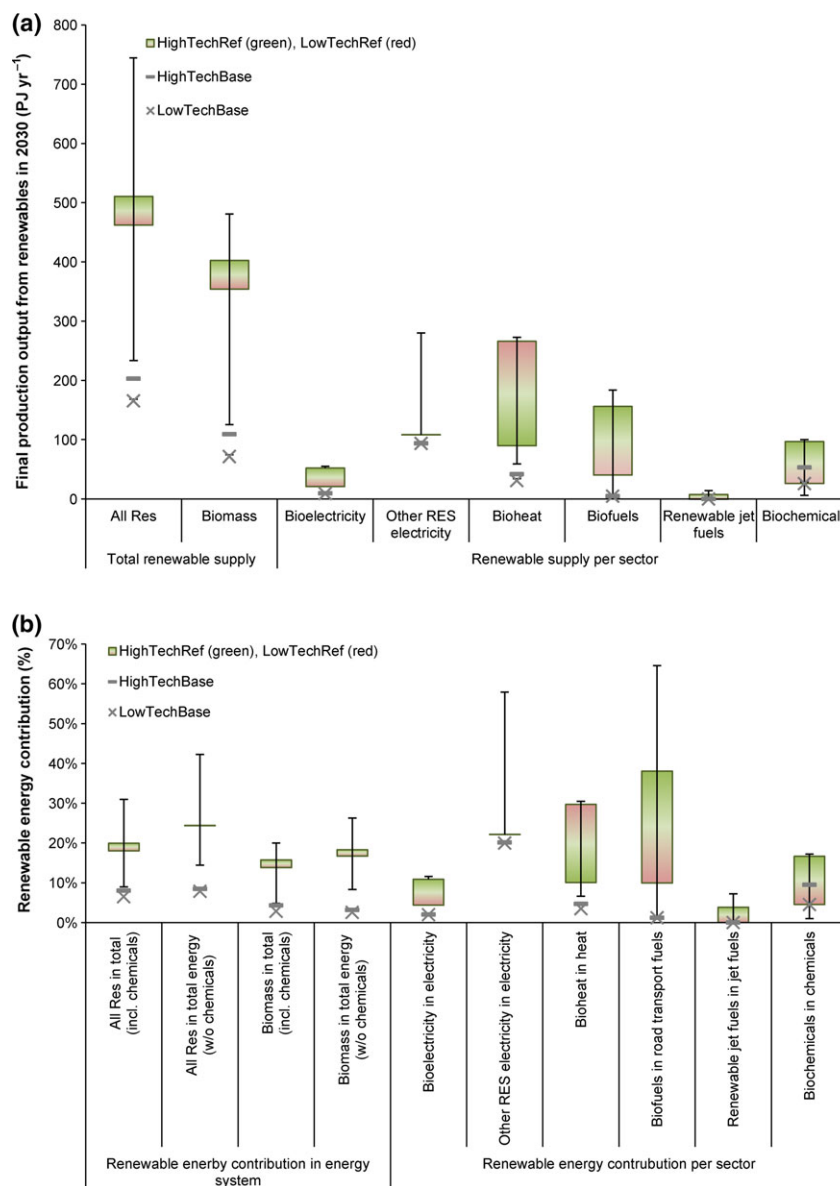
Biochemicals are produced even under *HighTechBase* and *LowTechBase* as a result of the retirement of steam-cracker capacity (20–50 PJ; 5–10% of the sector's output Fig. 4). While the CO<sub>2</sub> tax only affects the process emissions of the chemical sector, Fig. 4 shows that in *HighTechRef* the output of biochemicals almost doubles (about 100 PJ; 17%) compared to *LowTechRef*. This is a result of multi-output technologies that produce both chemicals and road transport fuels, with the latter being affected by the CO<sub>2</sub> tax.

The electricity sector is most sensitive to assuming high fossil fuel prices, which lead up to a factor 2.5

increase in electricity from other RES (primarily wind power) compared to reference scenarios. Regarding other scenario variants (e.g. low fossil fuel prices), electricity from other RES is not affected, as most of the wind capacity is installed by 2020 to confirm with Dutch EU RED targets.

Regarding electricity from biomass, at a sector level scenario variants, namely biomass cost-supply and fossil fuel prices, do not have significant influence, as ranges are found to be comparable with those of technology development scenarios (whiskers in Fig. 4a). Brouwer *et al.* (2016) suggest that low biomass prices could place electricity generation from biomass earlier in the merit order than electricity from natural gas; biomass could have a larger role in the electricity sector. Similarly, other assumptions, such as higher CO<sub>2</sub> emission taxes, or higher targets of RES for low-carbon power systems could lead to different outcomes regarding other RES (Brouwer *et al.*, 2016).

While in absolute terms, final energy supply from biomass per sector is comparable across all scenario variants (Fig. 4a), in relative terms, its contribution to the sector's final energy varies (Fig. 4b). Most notable is the contribution of biofuels to road transport fuels, which goes beyond 60% under *HighTech(RefBio\_HighFos)*. This occurs due to the increased biofuel supply (20% higher than in *HighTechRef*) and due to reduced fuel demand by the sector (roughly 1/3 or 130 PJ decrease compared to *HighTechRef*) as more efficient vehicles are deployed. These are primarily wheel motor hybrid vehicles with 76% higher efficiency compared to regular petrol cars found in reference scenarios (i.e. 927 compared to 526 km driven GJ<sup>-1</sup>; van Vliet *et al.*, 2011). While electrification of transport is included in the

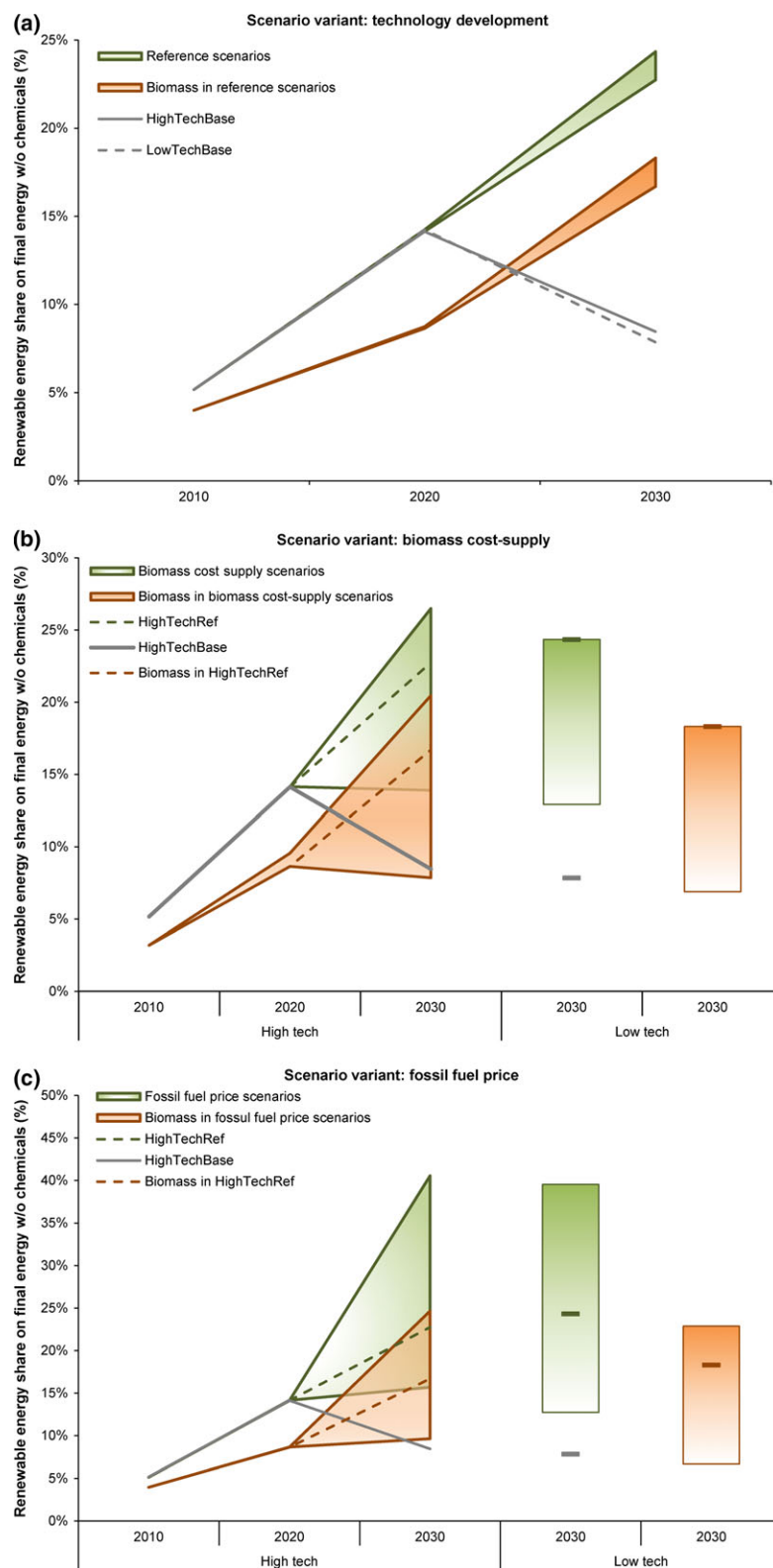


**Fig. 4** (a) Final renewable energy and nonenergy supply renewable resources in the energy system and per sector and (b) contribution of renewable energy and nonenergy in the energy system and per sector (remainder is fossil fuels) in the Netherlands in 2030. Bars indicate ranges of reference scenarios, whiskers indicate range of biomass cost-supply and fossil fuel price scenarios (see scenario descriptions in Table 1).

technology portfolio, model outcomes show that for the energy system of the Netherlands by 2030, biofuel supply in *HighTech* scenarios and efficient hybrid vehicles (in *HighTech(RefBio\_HighFos)*) is a more cost-effective option, partly owing to high costs of electric vehicles. This suggests that to increase electrification in transport, other support instruments are required (e.g. subsidies or tax exemptions).

The market constraint on individual second-generation biofuel technologies (section 'Rate of technology development and technology diffusion') limits the

production output of FT-fuels in *HighTechRef* and *HighTech(LowBio\_RefFos)*. In *HighTech(RefBio\_HighFos)*, it limits second-generation ethanol production due to the deployment of hybrid petrol engines for which ethanol is the substitute. Across scenarios, the share of first-generation biofuels over the total transport fuel supply is 1–13% (5–66 PJ) and 1–12% (5–55 PJ) in *LowTech* and *HighTech* scenario variants, respectively. In *LowTech* scenarios, all biofuels are supplied to road transport. In *HighTech* scenarios, 4–8 PJ of hydrotreated used cooking oil is supplied to aviation,



**Fig. 5** Renewable energy share on final energy and biomass contribution in the Netherlands in 2010–2030 under high technology development compared to low technology development in 2030 for (a) technology development (b) biomass cost-supply and (c) fossil fuel price scenarios. In the Low tech variant, grey markers indicate the baseline and green markers the reference result (see scenario descriptions in Table 1).

while the remainder of first-generation biofuels are supplied to road transport. The share of second-generation biofuels over the total transport fuel demand is 0–3% (0–15 PJ) and 10–29% (60–136 PJ) in *LowTech* and *HighTech* scenario variants, respectively. In *HighTech* variants, 6–8 PJ of FT-RJF are supplied to aviation, while the remainder of second-generation biofuels are supplied to road transport.

In *HighTech* scenarios, while the output of RJF (7–14 PJ) and biochemicals (22–100 PJ) to total final energy supply is relatively small, their contribution to their sectors is up to 7% and 17%, respectively. This is quite significant considering that today's output is limited and that within a 15-year timeframe, such developments can obtain a large market share.

Figure 5 shows the renewable energy share and the contribution of biomass in more detail. Biomass contributes more than two-thirds to the share of renewable energy in reference scenarios (Fig. 5a) and biomass cost-supply scenarios (Fig. 5b). Access to low-cost biomass increases the renewable energy share and the contribution of biomass by approximately 17% but only under *HighTech(LowBio\_RefFos)*. Under limited access to low-cost biomass, the contribution of renewable energy in 2030 is maintained similar to 2020 levels, that is 14% share from RES, where biomass supplies approximately 50% of renewable energy. Under *LowTech(LowBio\_RefFos)* access to low-cost biomass does not increase the RES share or its contribution. Restricted access to low-cost supply coupled with low technology development can pose barriers to cost-efficient deployment of biomass in the Netherlands.

Fossil fuel price variation leads to wider ranges (Fig. 5c). First and foremost, under high fossil fuel prices the renewable energy share almost doubles compared to reference scenarios; biomass contribution does not follow the same relative growth due to the increase in electricity from wind turbines in the energy system. Under *HighTech(RefBio\_LowFos)* and *LowTech(RefBio\_LowFos)*, RES and biomass contribution remain in 2020 levels for, similar to *HighTech(LowBio\_RefFos)* and *LowTech(LowBio\_RefFos)*.

#### Biomass consumption

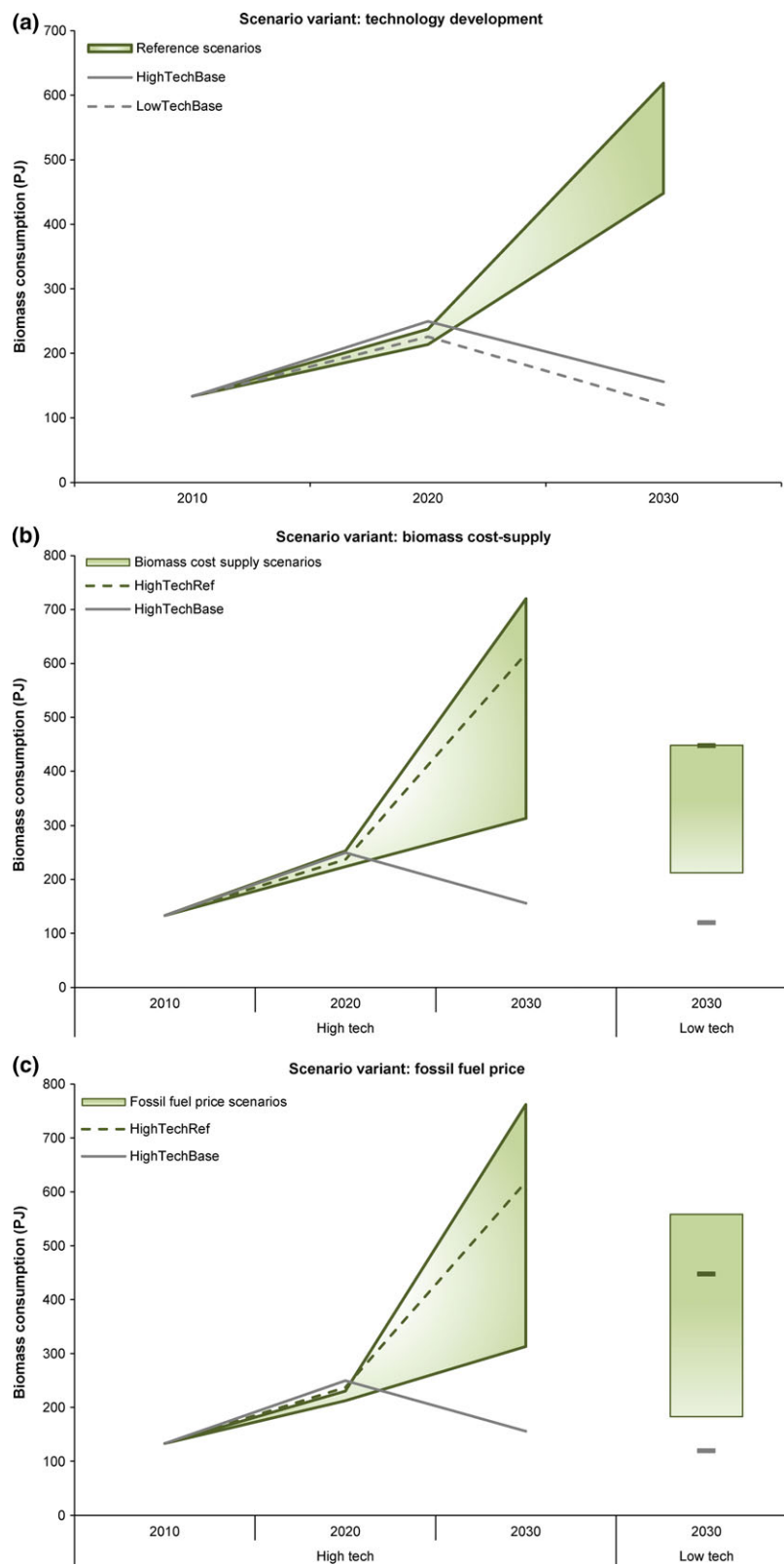
Early in the time horizon (2020), biomass consumption driven by technology development is relatively small, at approximately 200 PJ in both technology development scenarios and is comparable to baseline projections. Nevertheless a factor 2 growth is observed compared to 2010. By 2030, due to the CO<sub>2</sub> tax, biomass consumption is 330–460 PJ higher than the baseline (Fig. 6a).

Access to low-cost biomass shows that additional 100 PJ are used in the energy system (Fig. 6b), however, only under *HighTech(LowBio\_RefFos)*. Total biomass consumption exceeds 700 PJ, which as seen in Fig. 5b also increases by roughly 4% the contribution of RES and biomass to the energy system. On the other hand, high biomass costs can reduce consumption levels significantly (to slightly above 300 PJ) even *HighTech(HighBio\_RefFos)*. The range found between *LowTech(HighBio\_RefFos)* and *LowTech(LowBio\_RefFos)* by 2030 is significantly smaller than the one found between *HighTech(HighBio\_RefFos)* and *HighTech(LowBio\_RefFos)*, that is 240 PJ compared to 400 PJ. *HighTech* leads to growth in biomass consumption but *LowTech* leads to fairly constant consumption levels between 2020 and 2030. The above indicates that *LowTech* could impede long-term bioeconomy growth as indicated by biomass consumption.

Biomass consumption is also highly sensitive to the assumed level of fossil fuel prices to 2030 (Fig. 6c; reference fossil fuel prices: oil 13.4 € GJ<sup>-1</sup>, natural gas 7.3 € GJ<sup>-1</sup>, coal 3.1 € GJ<sup>-1</sup> in 2030, see Fig. 2). For *LowTech* and *HighTech* scenarios, biomass consumption is more sensitive to low than high fossil fuel price assumptions. A 50% increase in fossil fuel prices leads to approximately 25% increase in biomass consumption in *HighTech(RefBio\_HighFos)* and *LowTech(RefBio\_HighFos)* compared to *HighTechRef* and *LowTechRef*, respectively (indicated in Fig. 6c by the area above the dotted line and the upper marker in high and low technology development, respectively). Low fossil fuel prices lead to 50–60% reduction of biomass consumption found in reference scenarios. *HighTech(RefBio\_HighFos)* and *HighTech(RefBio\_LowFos)* lead to similar consumption levels with *HighTech(LowBio\_RefFos)* and *HighTech(HighBio\_RefFos)*, respectively (Fig. 6b, c). Therefore, even under unfavourable conditions induced by low fossil fuel prices, high technology development scenarios demonstrate small but stable growth in biomass consumption. On the contrary, *LowTech(RefBio\_HighFos)* consumes maximum 560 PJ under most favourable conditions induced by high fossil fuel prices, which are comparable to *HighTechRef* (the upper range of the bar is comparable to the upper range of the dotted line in Fig. 6c).

#### CO<sub>2</sub> emissions

In Fig. 7a, it is shown that the CO<sub>2</sub> tax leads to emission reduction compared against projected baseline emissions in the range of 35–43% for *LowTechRef* and *HighTechRef*, respectively. Compared to *LowTechRef*, the additional emission reduction in *HighTechRef* is 15 Mt CO<sub>2</sub>. The decreasing trend in emissions is steeper beyond 2020 as a result of higher CO<sub>2</sub> tax levels and



**Fig. 6** Biomass consumption in the Dutch bioeconomy in 2010–2030 under high technology development compared to low technology development in 2030 for (a) technology development (b) biomass cost-supply and (c) fossil fuel price scenarios (see scenario descriptions in Table 1). In the Low tech variant, grey markers indicate the baseline and green markers the reference result.

additional technological options. Nevertheless, even under *HighTechRef* additional 20 Mt CO<sub>2</sub> emission reduction is required to reach the 40% emission reduction target compared to 1990. *HighTech(LowBio\_RefFos)* leads to additional 5 Mt CO<sub>2</sub> reduction, partly bridging the gap with the target (Fig. 7b). As *LowTech(LowBio\_RefFos)* does not utilize additional low-cost biomass compared to *LowTechRef* (Fig. 6b), no additional emission reduction is achieved (Fig. 7b). *HighTech(HighBio\_RefFos)* leads to emission reduction levels comparable with those achieved in *LowTechRef* (i.e. approximately 35% compared to the baseline or direct CO<sub>2</sub> emissions in the range of 120 Mt CO<sub>2</sub>). Similar reduction is observed in *HighTech(RefBio\_LowFos)* (Fig. 7c). However, under such circumstances, the distance to the 40% emission reduction target is 30% (or 40 Mt CO<sub>2</sub>). To remain in cost-efficient emission reduction trajectories, *HighTech* seems to be a no-regret solution even under unfavourable conditions shaped by high-cost biomass or low fossil fuel prices as they offer significant potential for deeper emission reduction. More specifically, results indicate that under *HighTech(RefBio\_HighFos)*, the 40% emission reduction target is reached. In *LowTech(RefBio\_HighFos)*, however, CO<sub>2</sub> mitigation is 12 Mt CO<sub>2</sub> behind the target (Fig. 7c). Note that these emissions exclude those that occur outside the geographical boundaries of the Netherlands from production and transport of biomass, land-use change, extraction and transport of fossil fuels and jet fuels (section 'Indicators and overview of the modelling framework').

Figure 8 shows the amount of carbon captured and stored by CCS and BECCS across the different scenarios (19–41 Mt CO<sub>2</sub>). The contribution of CCS and BECCS in emission reduction is significant (42–60% compared to the baseline). The remainder of emission reduction is primarily achieved through biomass (20–40 Mt CO<sub>2</sub>), as with the exception of high fossil fuel price scenarios, the capacity of wind and other RES does not increase significantly compared to the baseline.

Carbon capture and storage is stimulated by the high CO<sub>2</sub> tax while in baseline scenarios, no CCS is deployed. The key difference across *HighTechRef* and *LowTechRef* is the deployment of BECCS in gasification technologies that supply FT-fuels to the transport sector. These technologies are assumed not to be available in *LowTech* scenarios. Carbon capture by the power sector is primarily associated with retrofitted coal-based power plants. It represents more than 65% of the emissions captured and stored by the sector. The remainder is associated with gas-based capacity and is similar across the technology development scenarios. In *HighTech* scenarios, BECCS represent 16–50% of the emissions captured and stored.

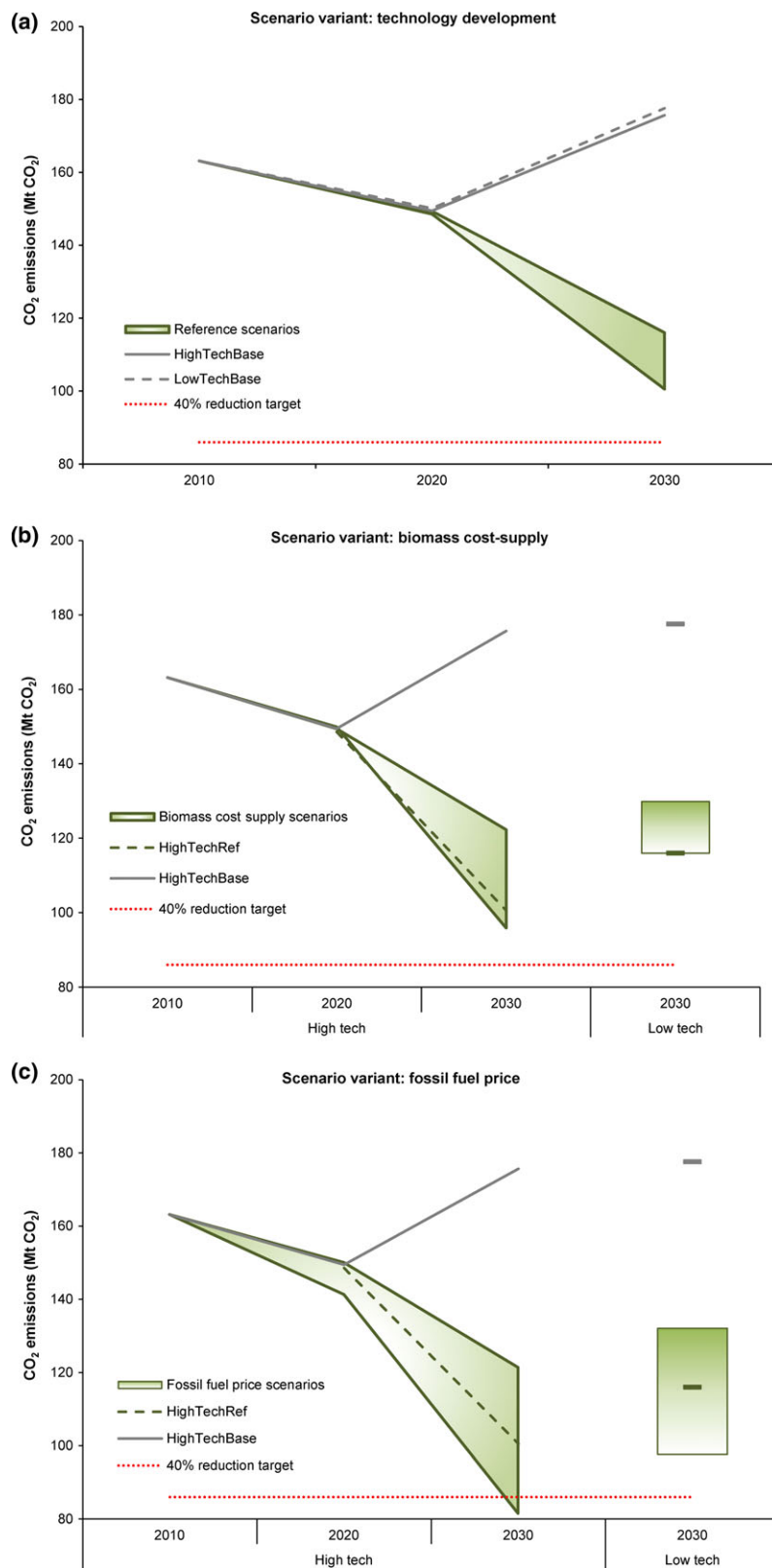
In scenarios that assume high fossil fuel prices, CCS in *LowTech(RefBio\_HighFos)* and in addition BECCS in *HighTech(RefBio\_HighFos)* represent 10–20% of the emission reduction achieved compared to the baseline (10–20 Mt CO<sub>2</sub> is stored). In these scenarios, significant emission reduction is achieved through other RES, as the output of wind electricity increases by approximately a factor 3, compared to the baseline (emission reduction from bioenergy and other RES is 70–75 Mt CO<sub>2</sub>). In addition, less coal capacity is projected to be used. Due to the decrease in demand for transport fuels by deployment of efficient vehicles the transport sector also contributes to emission reduction.

### System costs

We compare total annual system costs and total direct CO<sub>2</sub> emissions in 2030 between all scenario variants and *HighTechBase* (Fig. 9). Total system costs in most scenarios increase from 0.6 to 13.1 billion € yr<sup>-1</sup> compared to *HighTechBase*. An exception are *LowTech(RefBio\_LowFos)* and *HighTech(RefBio\_LowFos)* that show lower costs of about 6.5 billion € yr<sup>-1</sup>. Annual system costs are most sensitive to fossil fuel price variation. A 35% decline in oil prices (section 'Fossil fuel prices'; Fig. 2) reduces annual system costs by about 9% and a 50% increase in oil prices increases annual system costs by approximately 18–19% in 2030, compared to *HighTechBase* (Table S12). *HighTech* scenarios consistently show lower system costs and CO<sub>2</sub> emissions in 2030 and cumulative system costs and CO<sub>2</sub> emissions over the period 2010–2030 (Table S11) when compared to their *LowTech* scenario counterparts. This illustrates that *HighTech* is a no-regrets solution also when costs are taken into account. Note that total system costs do not include technology development costs (e.g. R&D, 1st-of-a-kind plant, production at low capacity factors or high downtime) nor investment and dismantling lead-times and costs. As technology development occurs in larger regions and cannot be allocated to the Netherlands, these costs are excluded from both *LowTech* and *HighTech* scenarios and are not expected to affect the relative conclusions drawn in this study. Including such costs requires a modelling framework with a wider regional scope. In absolute terms, however, should investment and dismantling costs be included they would increase total system costs.

### Other scenarios

*Low demand for chemicals.* Figure 10 shows a decline in demand for chemicals over time, which in combination with delayed decommissioning of old steam cracking capacity in the Netherlands beyond 2030 affects the production output of biochemicals. This is noticed early in



**Fig. 7** CO<sub>2</sub> emissions in the Netherlands in 2010–2030 under high technology development compared to low technology development in 2030 for (a) technology development (b) biomass cost-supply and (c) fossil fuel price scenarios (see scenario descriptions in Table 1). In the Low tech variant, grey markers indicate the baseline and green markers the reference result.

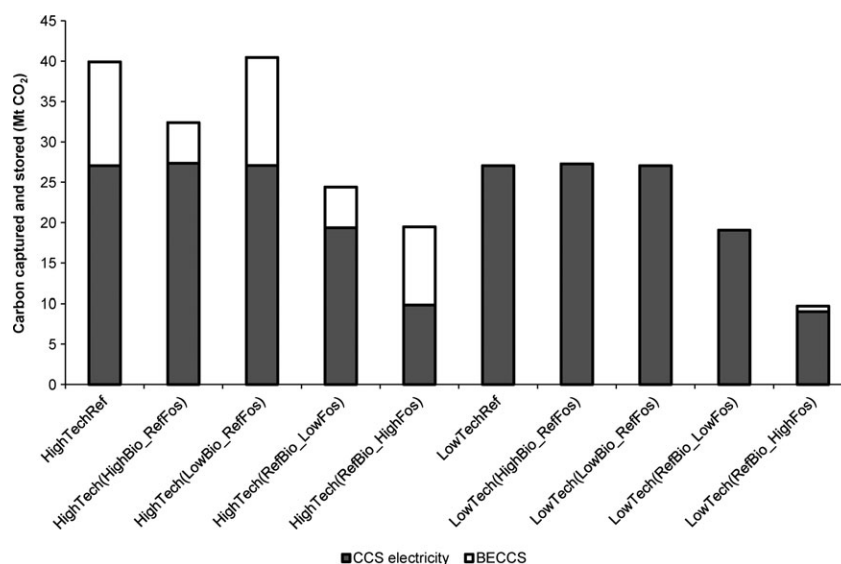


Fig. 8 Carbon captured and stored across different scenario variants in the Netherlands in 2030.

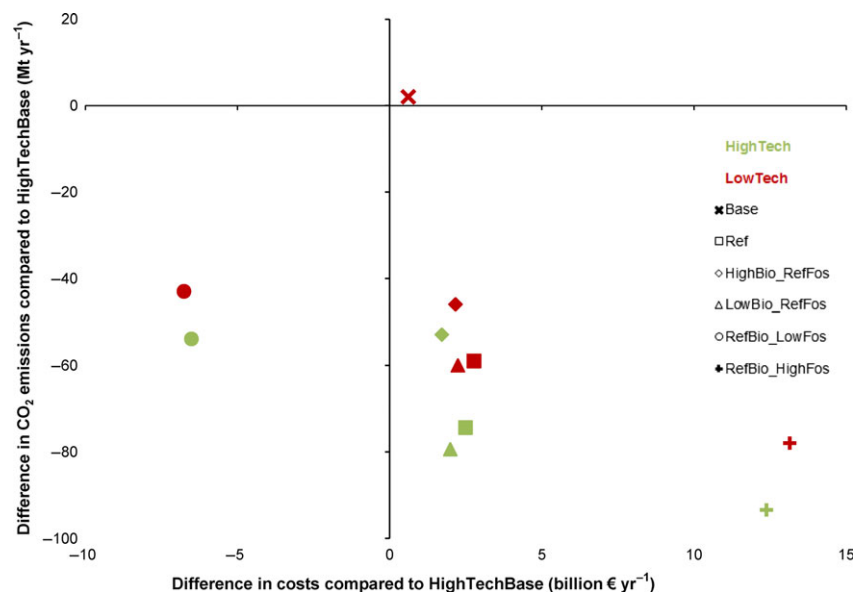
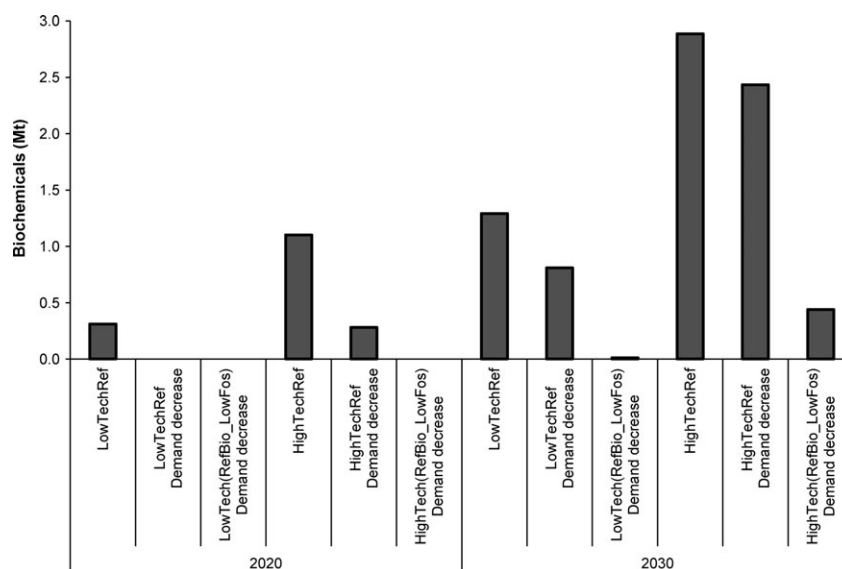


Fig. 9 Difference of total annual system costs and total direct emissions in 2030 between HighTechBase and the other scenario variants.

the time horizon (2020), when under *LowTech* assumptions, no production of biochemicals takes place, and under *HighTech* assumptions, the production output is reduced by 75% compared to *HighTechRef*. The difference in production output between scenarios becomes smaller by 2030, and lower demand for petrochemicals leads to a 16–37% reduction of output in *LowTech* and *HighTech* compared to their reference. However, assuming low fossil fuel prices creates an uncompetitive environment for biochemicals throughout the modelling period. This may be also an outcome of the limited

number biochemicals that are assumed in this study combined with the fact that the CO<sub>2</sub> tax does not affect nonenergy use (i.e. biochemicals do not receive any credit for their bio-based carbon content). As Fig. 11 shows, assuming lower demand for chemicals does not affect the direct CO<sub>2</sub> emissions of the Dutch energy system. Compared to their reference scenarios, the low chemical demand scenarios lead to 4–5% lower CO<sub>2</sub> emissions, primarily due to less process energy emissions (electricity, heat) as a result of decrease in industrial demand for energy.





**Fig. 10** Biochemical output in reference and low fossil fuel price scenarios assuming different growth rates for the chemical industry in the Netherlands in 2020–2030.

*Decommissioning of coal-based power capacity.* The results show that decommissioning coal-fired power stations in the Netherlands after 2020 increases wind electricity by 55–75% (48–65 PJ; offshore wind turbine capacity increase of 5.2 GW<sub>e</sub> and 3.9 GW<sub>e</sub> in low and high technology development, respectively, compared to *LowTechRef* and *HighTechRef*, respectively) and 13–18% (30–39 PJ) in natural gas-based electricity. By 2030, offshore wind turbines are expected to become more cost-efficient than other electricity production options leading to higher renewable energy share and contribution in the electricity sector. Deployment of onshore wind reaches constraint levels (8 GW<sub>e</sub>) across all scenarios with high CO<sub>2</sub> tax by 2030. Despite the significant deployment of wind power, direct CO<sub>2</sub> emissions remain at levels comparable with *LowTechRef* and *HighTechRef* because CCS combined with coal power plants is no longer an available mitigation option (Table S12). Overall the total carbon removed and stored by CCS is lower by 15 Mt CO<sub>2</sub> and 12.5 Mt compared to *LowTechRef* and *HighTechRef*, respectively. Decommissioning coal power plants leads to additional system costs of 6.7–9 M€ yr<sup>-1</sup> from 2020 onward and increases CO<sub>2</sub> mitigation costs by 12% and 14% in *HighTechRef* and *LowTechRef*, respectively (Tables S12 and S13).

## Discussion

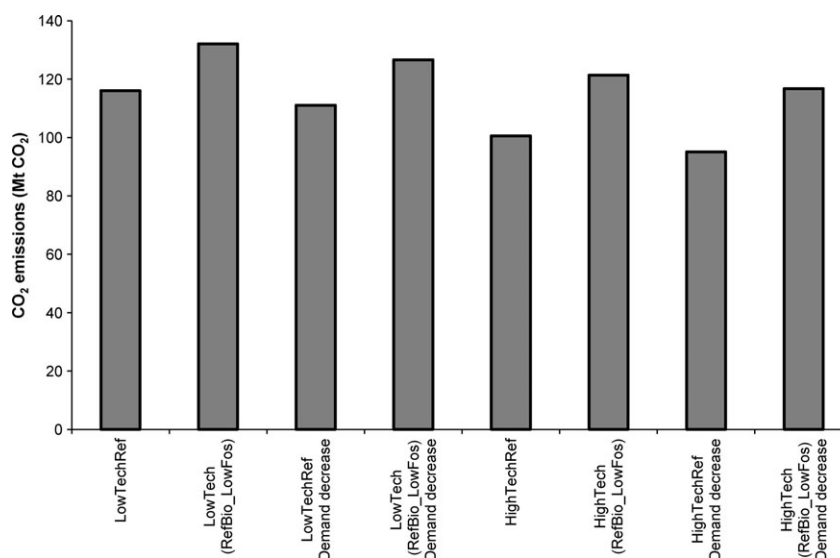
This study compared multiple scenario outcomes of an energy systems model to gain insights in CO<sub>2</sub> emission reduction that can be achieved by renewable energy, CCS and BECCS deployment in the energy system

when driven by cost competition with fossil fuel alternatives. We used the MARKAL-NL-UU model, which includes a representation of modern and emerging biomass conversion technologies, other renewable and fossil fuel conversion technologies. We did not incorporate any policy assumptions beyond 2020 to allow for free competition between all options. Using CO<sub>2</sub> tax as the only instrument for emission reduction, we assessed the achievement of or the distance to the EU's 40% emission target in 2030 compared to 1990.

We incorporated different biomass cost-supply curves to assess how deployment of biomass conversion technologies at a sectoral level and emission reduction at a systems level can be affected. We also assessed how dependent the national bioeconomy and the renewable energy system is on fossil fuel price variation. By combining biomass cost-supply and fossil fuel price scenarios with different assumptions on technology development, which vary in learning progress and technical parameters of technologies, we captured key uncertainties of mid-term bioeconomy development.

There are important considerations that should be taken when interpreting the outcomes.

Firstly, we used CO<sub>2</sub> emission pricing as the instrument to stimulate emission reduction as opposed to applying a cap on national emissions. In most scenarios, the 40% emission reduction target is not reached albeit significant reduction is realized (46–97 Mt CO<sub>2</sub> across scenarios compared to baseline; Fig. 7). The CO<sub>2</sub> price assumptions of IEA-WEO 2015 reflect the EU and not the required level for an individual country such as the



**Fig. 11** Direct CO<sub>2</sub> emissions in reference and low fossil fuel price scenarios assuming different growth rates for the chemical industry in the Netherlands in 2020–2030.

Netherlands to achieve the target. Evidently, a higher CO<sub>2</sub> price would be required for the Netherlands. In addition, the assumed CO<sub>2</sub> price is an outcome of simulation where other policy measures and technologies such as energy efficiency are taken into account. Such measures are not included in our model. It could be argued that the assumed CO<sub>2</sub> price would be adequate to achieve the target in all scenarios had low-cost efficiency measures such as insulation of buildings been included. Then, the abatement achieved by biomass, other RES, CCS and BECCS could be lower. Related to the above, is that the CO<sub>2</sub> tax is assigned on sectoral emissions and not on the fossil carbon they consume. This is relevant for the chemical sector, which consumes large volumes of fossil carbon as feedstock that remains embedded in the products. Applying the tax on fossil carbon consumption similar to other studies (Daioglou *et al.* (2014)) could lead to different system dynamics because the benefit of avoiding CO<sub>2</sub> emissions from waste management would be taken into account. However, for a national model, this entails an improved representation of the end-of-life phase of products, where cascading uses and exports of chemicals are taken into account (Tsiropoulos 2016). This study finds that significant volumes of biochemicals could potentially be produced by 2030 (5–20% of total chemical output in final energy terms; Fig. 4b), even under baseline assumptions (5–10% of total chemical output in final energy terms; Fig. 4b). This entails that there may be a high potential for cascading uses of biomass from higher to lower value applications (Keegan *et al.*, 2013). While this is not modelled in the study, it is important to point out that cascading uses would lead to increase in efficient

biomass use in the energy system and possibly to an increased output of biomass heat and electricity. Note that, based on Dammer *et al.* (2013), the production capacity of biochemicals in the Netherlands is comprised primarily of starch-blends and functional polymers (approximately 0.13 Mt). These applications are excluded from our study as we focus on large-scale production of biochemicals with significant potential for the substitution of fossil energy in the chemical industry. A combination of factors such as delayed retirement of steam cracking capacity, low fossil fuel price environment and decline in demand have an impact on the competitiveness of biochemicals as the output becomes negligible. Regarding the aviation sector, it was found that RJF may be supplied only under high technology development assumptions.

Furthermore, the outcomes represent only domestic emissions that occur in the Netherlands. The emissions related to production and transport of fossil fuels and biomass outside the Netherlands are not included. Consequently, neither are emissions from direct and indirect land-use change. Emissions from indirect land-use change are rather uncertain (Wicke *et al.*, 2012). However, the present study demonstrates that large volumes of biomass may be consumed in the Netherlands in the mid-term and direct as well as indirect land-use change emissions may influence global CO<sub>2</sub> emission reduction efforts. In Tsiropoulos (2016), we showed that emissions from production and import of biomass from regions outside the Netherlands were approximately 4 Mt CO<sub>2</sub>, which are 4–9% compared to the emission reduction achieved across scenarios from the baseline of this study. These emissions do not affect the main

conclusions drawn in this study, as they do not affect domestic emissions and distance to target. However, they are relevant when emissions at a larger geographical scope are assessed. Finally, non-CO<sub>2</sub> emissions (e.g. methane, nitrous oxides), from agriculture, industry and waste processing, while not related to the energy system that is assessed in the present study, accounted for about 16% (or 30 MtCO<sub>2eq.</sub>) of national total GHG emissions in 2014 (Table S9). It is estimated that over time it is technically feasible and cost-effective for these sectors to achieve approximately 50% emission reduction (Roelofsen *et al.*, 2016).

While the above are important to consider, this study shows results that are well-aligned with other efforts.

A study that assessed lowest-cost complementarity of integrating fossil-based capacity with predetermined RES diffusion to achieve low-carbon power systems illustrates the significance of wind turbines and CCS to achieve emission reduction (Brouwer *et al.*, 2016). While there are key differences in scope (geographical, temporal) and modelling techniques between the present study and Brouwer *et al.* (2016), they both show that lowest system costs are achieved with a mix of RES and CCS in the power sector. Similar outcomes are supported by van den Broek *et al.* (2011) in scenarios which take ambitious climate policies into account. A key difference between the outcomes of these studies compared to the results presented here is the deployment of CCS in gas-fired instead of coal-fired plants. An explanation to this can be the recent instalment of coal-based capacity in the Netherlands, which remains operational until 2030. An additional explanation could be that in the present study, more sectors are included in the energy system. As van Vliet *et al.* (2011) showed, when accounting for the transport sector in the energy system, the role of BECCS in biomass-based FT-fuel production is prominent. This finding, as confirmed by the present study, is also relevant when emerging bioeconomy sectors (i.e. biochemicals and RJF) are included in the energy system. Therefore, the significance of BECCS is demonstrated not only as a longer-term emission mitigation option, which many studies support (Fischedick *et al.*, 2011; Fuss *et al.*, 2014), but also in earlier in the time horizon, provided that the technology can be commercialized within the assumed timeframe.

Regarding biochemicals, to our knowledge there are limited studies that provide future estimates at a systems level, as for example Daioglou *et al.* (2014). According to their study, in the long term biomass has the potential to supply up to 40% of total demand for nonenergy in 2100 (or about 1 Gt yr<sup>-1</sup> assuming 45 GJ t<sup>-1</sup> as heating value; Daioglou *et al.*, 2014). Other studies have also performed short-term assessments of future biochemical potential (Dornburg *et al.*, 2008; Ren

& Patel, 2009; Ren *et al.*, 2009; nova-Institut, 2013; Saygin *et al.*, 2013, 2014; Gerssen-Gondelach *et al.*, 2014; Piotrowski *et al.*, 2015) without, however, taking systems dynamics into account. European Bioplastics estimate that global production capacity of bioplastics will reach 7.85 Mt in 2019 (EuBP, 2016). Our study estimates that production output of biochemicals may reach up to 1.1 Mt in the Netherlands in 2020 depending on scenario conditions. While results of these studies cannot be directly comparable with the output of this study, they all confirm that biochemical increases over time.

Against this background, the most important observations can be summarized in the following:

*The size of bioeconomy depends on developments across the supply chain and the fossil fuel price*

By 2030, the contribution of biomass in renewable energy supply is higher than the approximately 50% that is anticipated according to other studies by 2020 (Rijksoverheid, 2010; Stralen *et al.*, 2013). It ranges between 52% and 77% and corresponds to biomass consumption volumes of 183–760 PJ, depending on scenario assumptions. Biomass supply depends on intra-EU and extra-EU biomass, and based on literature, it is deemed available (Chum *et al.*, 2011; Ganzevles, 2014; Smeets, 2014). The supply from RES observed in the decade 2020–2030 is due to technological growth and increase in the CO<sub>2</sub> emission tax. Other RES remain fairly constant to 2020 levels, while the bioeconomy grows. Investments across the supply chain both on the supply side, as modelled by the low-cost biomass scenario, and on the conversion side, as modelled by the high technology development scenario, lead to increased contribution of biomass in the system (Fig. 6a). Low fossil fuel prices do not lead to contraction of the RES share compared to 2020 and reduce total system costs by about 6.5 billion € yr<sup>-1</sup> in 2030, however, even under high technology development no growth is observed. In the face of low fossil fuel prices, mechanisms are required to ensure bioeconomy growth such as a CO<sub>2</sub> tax higher than 69 € t<sup>-1</sup> CO<sub>2</sub> by 2030.

*A mixed technology portfolio is required to achieve deep emission reduction*

A wide technology portfolio is required to achieve emission reduction in the mid-term, to realize long-term climate goals. The role of wind in the electricity sector, bioenergy in road transport and industrial heat, but also CCS and BECCS are significant. This finding is widely supported by literature (IPCC, 2014; Matthews *et al.*, 2015; Winchester & Reilly, 2015). Introducing new bioeconomy sectors in the energy system, namely

biochemicals and RJF does not alter it; however, the latter are supplied only under high technology development assumptions. As other RES do not increase significantly in the scenario outcomes, except when high fossil fuel prices are assumed, the post-2020 emission reduction can be attributed to biomass (20–40 Mt CO<sub>2</sub> or 40–60% compared to the baseline) and CCS (19–41 Mt CO<sub>2</sub> or 42–60% compared to the baseline). In high technology development scenarios, which among other options include BECCS, emission reduction is higher by 6–17% (7.5–20 Mt) compared to low technology development scenarios (BECCS contributes 47–83%). BECCS can have a significant role earlier in the time horizon than most studies indicate (Fischedick *et al.*, 2011; Fuss *et al.*, 2014), if the technology is commercialized. With demand-side improvements (e.g. on industrial and residential energy efficiency), the role of biomass heat may diminish in the longer term. This could create opportunities for other bioeconomy sectors to grow. Such an assessment requires incorporation to the model of energy efficiency measures or a longer temporal scope (e.g. 2040), which may also result in other structural changes of sectors such as electrification in transport.

#### *Sector-specific assumptions do not compromise the potential emission reduction*

A decrease in demand for chemicals in combination with other factors such as delayed retirement of steam cracking capacity and low fossil fuel prices affects the size of the biochemical sector. The latter reduce the output of biochemicals by about 70% compared to the reference, while combined with the former assumptions the reduction ranges between 85 and 99%. However, the systems' CO<sub>2</sub> emissions are not affected. Furthermore, dismantling all coal-based power generation capacity leads to an increase in RES (wind) and natural-gas power generation. While coal is effectively phased out entirely from the energy system of the Netherlands, the emission levels in 2030 remain the same as CCS capacity compared to reference scenarios is lower and the emission reduction is offset by wind turbines.

#### *High technology development is a no-regrets option to achieve deep emission reduction*

Post-2020, high technology development uses 313–760 PJ of biomass depending on scenario assumptions. Compared to the low technology development counterparts, it offers additional opportunities to utilize biomass in the energy system as indicated by the additional 100–270 PJ that are consumed. High technology development combined with the low-cost biomass

scenario uses approximately 100 PJ more compared to the reference. Assuming low-cost biomass does not lead to increased consumption in low technological growth scenarios. Thus, improvements early in the supply chain increase the size of the bioeconomy only under high technological growth. Furthermore, high technology development consistently leads to lower emissions and cumulative system costs than low technology development in 2030. At the same time, high technology development creates a more resilient bioeconomy even if fossil fuel prices remain low as there is continuous growth to 2030. However, this observation excludes external costs, which are required to achieve high technological growth, such as in R&D or support to 1st-of-a-kind plant. Furthermore, this comparison is sensitive to the underlying production costs of bioenergy and biochemicals as illustrated by the two technology development scenario variants. Nonetheless, to achieve deeper levels of emission reduction required to embark on low-cost trajectories that meet long-term climate targets technological development is required to reduce production costs of advanced biomass conversion technologies.

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#### References

- AEBIOM (2015) *AEBIOM Statistical Report – European Bioenergy Outlook*. European Biomass Association (AEBIOM), Brussels, Belgium.
- Batidzirai B, Van Der Hilst F, Meerman H, Junginger MH, Faaij APC (2014) Optimization potential of biomass supply chains with torrefaction technology. *Biofuels, Bioproducts and Biorefining*, **8**, 253–282.
- BCG (1968) *Perspectives on Experience*. Boston Consulting Group Inc (BCG), Boston, MA.
- van den Broek M, Faaij A, Turkenburg W (2008) Planning for an electricity sector with carbon capture and storage. Case of the Netherlands. *International Journal of Greenhouse Gas Control*, **2**, 105–129.
- van den Broek M, Veenendaal P, Koutstaal P, Turkenburg W, Faaij A (2011) Impact of international climate policies on CO<sub>2</sub> capture and storage deployment. *Energy Policy*, **39**, 2000–2019.
- Broeren MLM, Saygin D, Patel MK (2014) Forecasting Glob developments in the basic chemical industry for environmental policy analysis. *Energy Policy*, **64**, 273–287.
- Brouwer AS, van den Broek M, Zappa W, Turkenburg WC, Faaij A (2016) Least-cost options for integrating intermittent renewables in low-carbon power systems. *Applied Energy*, **161**, 48–74.
- CBS (2016) *Statistics Netherlands: Total Final Consumption*. Centraal Bureau voor de Statistiek (CBS), The Hague/Herleen.
- Chèze B, Gastineau P, Chevallier J (2011) Forecasting world and regional aviation jet fuel demands to the mid-term (2025). *Energy Policy*, **39**, 5147–5158.
- Chum H, Faaij A, Moreira J *et al.* (2011) Bioenergy. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* (eds Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlomer S, von Stechow C), pp. 209–332. Cambridge University Press, Cambridge, UK and New York, NY.
- Daigoglou V, Faaij APC, Saygin D, Patel MK, Wicke B, van Vuuren DP (2014) Energy demand and emissions of the non-energy sector. *Energy & Environmental Science*, **7**, 482.

- Daiglou V, Wicke B, Faaij APC, van Vuuren DP (2015) Competing uses of biomass for energy and chemicals: implications for long-term global CO<sub>2</sub> mitigation potential. *GCB Bioenergy*, **7**, 1321–1334.
- Dammer L, Carus M, Raschka A, Scholz L (2013) *Market Developments and Opportunities for Biobased Products and Chemicals*. nova-Institut, Hürth.
- Dornbush V, Hermann BG, Patel MK (2008) Scenario projections for future market potentials of biobased bulk chemicals. *Environmental Science & Technology*, **42**, 2261–2267.
- EC (2003) *EU-15 Energy and Transport Outlook to 2030 (part II)*. European Commission (EC), Brussels, Belgium.
- EC (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009. *Official Journal of the European Union*, **140**, 16–62.
- EC (2011) *Launch of the European Advanced Biofuels Flightpath*. European Commission (EC), Brussels.
- EC (2015) *Intended Nationally Determined Contribution of the EU and its Member States*, pp. 1–5. European Commission (EC), Riga, Lithuania.
- ECN (2015) *MONITweb*. Energy Research Centre of the Netherlands (ECN), Petten, the Netherlands.
- Elbersen B, Startisky I, Hengeveld G, Geurissen L, Lesschen J (2015) *Outlook of spatial value chains in EU28 – Deliverable 2.3 of Biomass Policies Project*. Alterra – Part of Wageningen UR, Wageningen, the Netherlands and Laxenburg, Austria.
- EuBP (2016) *Bioplastics Facts and Figures*, pp. 1–6. European Bioplastics (EUBP), Berlin, Germany.
- Fischedick M, Schaeffer R, Adedoyin A *et al.* (2011) Mitigation potential and costs. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* (eds Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlomer S, von Stechow C), pp. 791–864. Cambridge University Press, Cambridge, UK and New York, NY.
- Fuss S, Canadell JG, Peters GP *et al.* (2014) Betting on negative emissions. *Nature Climate Change*, **4**, 850–853.
- Ganzevles J (2014) *Bijlage 1: Vraag en aanbod in Nederland in 2030*, pp. 1–17. Commissie Duurzaamheidsvraagstukken Biomassa, Nijmegen, the Netherlands.
- Gerssen-Gondelach SJ, Saygin D, Wicke B, Patel MK, Faaij APC (2014) Competing uses of biomass: assessment and comparison of the performance of bio-based heat, power, fuels and materials. *Renewable and Sustainable Energy Reviews*, **40**, 964–998.
- Hoefnagels R, Searcy E, Cafferty K, Cornelissen T, Junginger M, Jacobson J, Faaij A (2014a) Lignocellulosic feedstock supply systems with intermodal and overseas transportation. *Biofuels, Bioproducts and Biorefining*, **8**, 794–818.
- Hoefnagels R, Resch G, Junginger M, Faaij A (2014b) International and domestic uses of solid biofuels under different renewable energy support scenarios in the European Union. *Applied Energy*, **131**, 139–157.
- IPCC (2006) *Energy*. In: *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme* (eds Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K), pp. 1.1–6.14. Intergovernmental Panel on Climate Change to Institute for Global Environmental Strategies, Kanagawa.
- IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Core Writing Team, Pachauri RK, Meyer LA). IPCC, Geneva, Switzerland.
- Keegan D, Kretschmer B, Elbersen B, Panoutsou C (2013) Cascading use: a systematic approach to biomass beyond the energy sector. *Biofuels, Bioproducts and Biorefining*, **7**, 193–206.
- Matthews R, Mortimer N, Lesschen JP *et al.* (2015) *Carbon Impacts of Biomass Consumed in the EU: Quantitative Assessment October 2015*. Forest Research, Farnham.
- van Meijl H, Tsiropoulos I, Bartelings H *et al.* (2016) *Macro-economic Outlook of Sustainable Energy and Biorenewables Innovations (MEV II)*, pp. 1–168. LEI Wageningen UR (University & Research centre), Den Hague, the Netherlands.
- Moss RH, Edmonds JA, Hibbard KA *et al.* (2010) The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747–756.
- Nicola S, Andresen T (2015) Germany gives dirtiest coal plants six years for phase out. Bloomberg, Businessweek. Available at: <http://www.bloomberg.com/news/articles/2015-07-02/germany-to-close-coal-plants-in-effort-to-curb-pollution> (accessed 25 May 2016).
- nova-Institut (2013) *Bio-based Polymers – Production Capacity will Triple from 3.5 Million Tonnes in 2011 to Nearly 12 Million Tonnes in 2020*, pp. 1–13. nova-Institut, Hürth.
- OECD/IEA (2014) *World Energy Outlook 2014*. Organisation for Economic Co-operation and Development (OECD), International Energy Agency (IEA), Paris, France.
- OECD/IEA (2015) *World Energy Outlook 2015*. Organisation for Economic Co-operation and Development (OECD), International Energy Agency (IEA), Paris, France.
- OGJ (2012) Global ethylene capacity continues advance in 2011. *Oil & Gas Journal*, 78.
- Pieters J (2016) Dutch cabinet to close two more coal plants. NLtimes.nl. Available at: <http://nltimes.nl/2016/04/11/dutch-cabinet-to-close-two-more-coal-plants/> (accessed 26 May 2016).
- Piotrowski S, Carus M, Essel R (2015) Global bioeconomy in the conflict between biomass supply and demand. Nova Paper #7 on Bio-based Economy, 1–13.
- Ren T, Patel MK (2009) Basic petrochemicals from natural gas, coal and biomass: energy use and CO<sub>2</sub> emissions. *Resources, Conservation and Recycling*, **53**, 513–528.
- Ren T, Daniëls B, Patel MK, Blok K (2009) Petrochemicals from oil, natural gas, coal and biomass: production costs in 2030–2050. *Resources, Conservation and Recycling*, **53**, 653–663.
- Rijksoverheid (2010) *National Renewable Action Plan of the Netherlands*. Government of the Netherlands, the Netherlands.
- Roelofsens O, de Pee A, Speelman E (2016) *Accelerating the Energy Transition: Cost or Opportunity?*. McKinsey & Company, Amsterdam.
- Rose SK, Krieglner E, Bibas R, Calvin K, Popp A, van Vuuren DP, Weyant J (2014) Bioenergy in energy transformation and climate management. *Climatic Change*, **123**, 477–493.
- Saygin D, Patel MK, Tam C, Gielen DJ (2009) *Chemical and Petrochemical Sector Potential of best practice technology*. International Energy Agency (IEA), Paris, France.
- Saygin D, van den Broek M, Ramírez A, Patel MK, Worrell E (2013) Modelling the future CO<sub>2</sub> abatement potentials of energy efficiency and CCS: the case of the Dutch industry. *International Journal of Greenhouse Gas Control*, **18**, 23–37.
- Saygin D, Gielen DJ, Draeck M, Worrell E, Patel MK (2014) Assessment of the technical and economic potentials of biomass use for the production of steam, chemicals and polymers. *Renewable and Sustainable Energy Reviews*, **40**, 1153–1167.
- Schwartz P (1996) *The Art of the Long View: Planning for the Future in an Uncertain World*, pp. 1–24. Random House Digital Inc, New York, NY.
- SER (2013) *Energy Agreement for Sustainable Growth – Summary*, pp. 6–9. Sociaal Economische Raad (SER), The Hague.
- Smeets E (2014) *Bijlage 2: Beschikbaarheid van biomassa voor export naar Nederland*, pp. 1–20. Commissie Duurzaamheidsvraagstukken, The Hague.
- Sterl S, Höhne N, Kuramochi T (2016) *What Does the Paris Agreement Mean for Climate Resilience and Adaptation?*. New Climate Institute, Cologne, Berlin, Germany.
- Stralen JNP, Uslu A, Longa FD (2013) The role of biomass in heat, electricity, and transport markets in the EU27 under different scenarios. *Biofuels, Bioproducts & Biorefining*, **7**, 147–163.
- Tsiropoulos I (ed.) (2016) Emerging bioeconomy sectors in energy systems modelling – Integrated systems analysis of electricity, heat, road transport, aviation and chemicals: a case study for the Netherlands. In: *Emerging Bioeconomy – Assessing the Implications of Advanced Bioenergy and Biochemicals with Bottom-Up and Top-Down Modelling Approaches*, pp. 89–150. Utrecht University, Utrecht.
- UNFCCC (2015) *Adoption of the Paris Agreement*, 21st Conference of Parties, United Nations Framework Convention on Climate Change (UNFCCC), Paris.
- Uslu A, Faaij APC, Bergman PCA (2008) Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. *Energy*, **33**, 1206–1223.
- van Vliet O, van den Broek M, Turkenburg W, Faaij A (2011) Combining hybrid cars and synthetic fuels with electricity generation and carbon capture and storage. *Energy Policy*, **39**, 248–268.
- Vuuren D, Boot P, Ros J, Hof A, den Elzen M (2016) *Wat betekent het Parijsakkoord voor het Nederlandse langtermijn-klimaatbeleid?*. Planbureau voor de Leefomgeving (PBL), den Haag, the Netherlands.
- Wicke B (2011) *Bioenergy Production on Degraded and Marginal Land: Assessing its Potentials, Economic Performance, and Environmental Impacts for Different Settings and Geographical Scales*. Utrecht University, Utrecht.
- Wicke B, Verweij P, van Meijl H, van Vuuren DP, Faaij APC (2012) Indirect land use change: review of existing models and strategies for mitigation. *Biofuels*, **3**, 87–100.
- Winchester N, Reilly J (2015) *The Contribution of Biomass to Emissions Mitigation under a Global Climate Policy*. MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA.
- de Wit M, Faaij APC (2009) European biomass resource potential and costs. *Biomass and Bioenergy*, **34**, 188–202.
- de Wit M, Junginger M, Lensink S, Londo M, Faaij A (2010) Competition between biofuels: modeling technological learning and cost reductions over time. *Biomass and Bioenergy*, **34**, 203–217.
- Yeo S (2015) *In-depth: UK Pledges Coal Phase Out by 2025, but Uncertainty Remains*. CarbonBrief. Available at: <https://www.carbonbrief.org/in-depth-uk-pledges-coal-phase-out-by-2025-but-uncertainty-remains> (accessed 25 May 2016).

## Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

**Appendix S1.** Technology portfolio, input data and technology development scenarios.

**Table S1.** Overview of electricity and heat technologies included in MARKAL-NL-UU (Tsiropoulos, 2016).

**Table S2.** Overview of road and jet fuel production technologies included in MARKAL-NL-UU (Tsiropoulos, 2016).

**Table S3.** Overview of conventional and biomass conversion technologies to chemicals included in MARKAL-NL-UU (Tsiropoulos, 2016).

**Table S4.** Cost structures of electricity production technologies (van Vliet *et al.*, 2011; Brouwer *et al.*, 2015).

**Table S5.** Cost structures of road transport fuel technologies (van Vliet *et al.*, 2011).

**Table S6.** Cost structures of road transport and jet fuels.

**Table S7.** Cost structures of chemical production and other technologies (continued at next page).

**Table S8.** Final electricity and heat demand in MARKAL-NL-UU (Tsiropoulos, 2016).

**Table S9.** Total final consumption, energy consumption and greenhouse gas emissions in the Netherlands in 2014 (NEV, 2015; RIVM, 2016).

**Fig. S1.** Production demand for basic chemicals and ammonia assumed in MARKAL-NL-UU for the Netherlands in 2010–2030 (Tsiropoulos, 2016).

**Fig. S2.** Low technology development scenario (LowTech) for conversion technologies added in MARKAL-NL-UU.

**Fig. S3.** High technology development scenario (HighTech) for conversion technologies added in MARKAL-NL-UU.

**Appendix S2.** Results.

**Table S10.** Final renewable energy consumption per sector and scenario and total final renewable energy consumption (including chemicals) per scenario in the Netherlands in 2030.

**Table S11.** Final energy consumption per sector and scenario and total final energy consumption (including chemicals) per scenario in the Netherlands in 2030.

**Table S12.** Primary biomass consumption, direct CO<sub>2</sub> emissions and undiscounted total system costs per scenario in the Netherlands in 2030.

**Table S13.** Cumulative total system costs and cumulative total system direct CO<sub>2</sub> emissions in the Netherlands in 2010–2030.